

A GLOBAL PERSPECTIVE ON STAR FORMATION

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We outline a method to infer the global history of star formation in galaxies with input only from absorption-line observations of quasars. The application of the method to existing data leads to the conclusion that most stars formed at relatively low redshifts ($z \lesssim 2$). We combine the global rate of star formation with stellar population synthesis models to compute the mean comoving emissivity and mean intensity of background radiation from far-UV to far-IR wavelengths. These predictions are consistent with all the available measurements and observational limits, including recent results from *HST* and *COBE*.

1 Overview

This article concerns the evolution of, and relations between, various large-scale average properties of the population of galaxies as a whole. It is often convenient to express these “global” properties as mean comoving densities and to normalize them to the present closure density. We are particularly interested in the comoving densities of stars, gas, metals, and dust within galaxies, which we denote respectively by Ω_s , Ω_g , Ω_m , and Ω_d . The last three of these are meant to refer to the interstellar media (ISM) of galaxies, exclusive of the intergalactic medium (IGM), although in practice such a distinction may only be approximate. As defined here, Ω_m includes metals in both the gas and solid (i.e., dust) phases of the ISM. It is usually more informative to reexpress Ω_m and Ω_d in terms of the mean metallicity and mean dust-to-gas ratio, $Z \equiv \Omega_m/\Omega_g$ and $D/G \equiv \Omega_d/\Omega_g$. It is clear that all of these properties are related in the sense that, as new stars form, Ω_s will increase, while, in most cases, Ω_g will decrease, and Z and D/G will increase. One of our goals is to quantify such relations through the equations of “cosmic chemical evolution”.

Until recently, there were no emission-based estimates of the global rate of star formation $\dot{\Omega}_s$ at $z \gtrsim 0.3$. The reason for this is that samples of galaxies selected by emission become progressively incomplete and include only brighter objects at higher redshifts. In contrast, samples of galaxies selected by absorption against background quasars do not suffer from this bias. Such observations are exquisitely sensitive to small column densities of absorbing or scattering particles. In principle at least, they enable us to estimate Ω_g , Ω_m , and even Ω_d as functions of redshift. From these and the equations of cosmic chemical

evolution, we can then infer the global rate of star formation $\dot{\Omega}_s$. It is amusing to note that this idealistic program does not require the detection of a single stellar photon! Furthermore, if we are confident (or foolish) enough, we can combine our estimates of $\dot{\Omega}_s$ with stellar population synthesis models to compute the mean comoving emissivity \mathcal{E}_ν and the mean intensity of background radiation J_ν . One might then claim to have predicted the “emission history” of the universe from its “absorption history”. This article describes a first attempt by Yichuan Pei, Stéphane Charlot, and the author to carry out such a program; a complete account of our work is given in references 1 and 2. Some related material can be found in references 3–6.

2 Absorption-Line Systems

Before proceeding, it is worth recalling some facts about the statistics of absorption-line systems. Let $f(N_x, z)$ be the column density distribution of particles of any type x that absorb or scatter light. These might, for example, be hydrogen atoms ($x = \text{HI}$), metal ions ($x = m$), or dust grains ($x = d$). By definition, $H_0(1+z)^3|dt/dz|f(N_x, z)dN_xdz$ is the mean number of absorption-line systems with column densities of x between N_x and $N_x + dN_x$ and redshifts between z and $z + dz$ along the lines of sight to randomly selected background quasars. These lines of sight are very narrow (much less than a parsec across) and pierce the absorption-line systems at random angles and impact parameters. One can show that the mean comoving density of x is given by

$$\Omega_x(z) = \frac{8\pi G m_x}{3c H_0} \int_0^\infty dN_x f(N_x, z) N_x, \quad (1)$$

where m_x is the mass of a single particle (atom, ion, or grain). Equation (1) plays a central role in this subject. It enables us to estimate the mean comoving densities of many quantities of interest without knowing anything about the structure of the absorption-line systems. In particular, we do not need to know their sizes or shapes, whether they are smooth or clumpy, and so forth. A corollary of equation (1) is that the global metallicity, $Z \equiv \Omega_m/\Omega_g$, is given simply by an average over the metallicities of individual absorption-line systems weighted by their gas column densities.

The absorption-line systems of most interest in the present context are the damped Ly α (DLA) systems. It is widely believed that they trace the ISM of galaxies and protogalaxies and are the principal sites of star formation in the universe. There are excellent reasons to adopt this as a working hypothesis. First, the DLA systems have, by definition, $N_{\text{HI}} \gtrsim 10^{20} \text{ cm}^{-2}$, which is just below an apparent threshold for the onset of star formation⁷. Second, the DLA

systems contain at least 80% of the HI in the universe and appear to be mostly neutral⁴. The other absorption-line systems, those with $N_{\text{HI}} \lesssim 10^{20} \text{ cm}^{-2}$, probably contain more gas in total than the DLA systems, but this must be diffuse and mostly ionized. In the following, we regard non-DLA systems as belonging to the IGM, even though some of them might actually be located in the outer halos of galaxies. This distinction – between the mostly-neutral ISM, where stars form, and the mostly-ionized IGM, where they do not – is clearly valid at the present epoch. Thus, the DLA systems are often referred to as DLA galaxies. It will be interesting to see exactly which types of galaxies they represent, but as we have already emphasized, this issue does not affect any of the global properties derived from equation (1).

The sample of known DLA galaxies now includes about 80 objects⁸. They are distributed over a wide range in redshift, $0 \lesssim z \lesssim 4$, although, as a consequence of selection effects, most of them are confined to the narrower range $2 \lesssim z \lesssim 3$. From observations of DLA galaxies in various subsets of this sample and comparisons with present-day galaxies, the following trends have emerged. The mean comoving density of HI decreases by almost an order of magnitude, from $\Omega_{\text{HI}} \approx (1 - 2) \times 10^{-3} h^{-1}$ at $z \approx 3$ to $\Omega_{\text{HI}} \approx 2 \times 10^{-4} h^{-1}$ at $z = 0$ [with $h \equiv H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$]^{4,8,9}. It is possible that Ω_{HI} increases between $z \approx 4$ and $z \approx 3$, but the evidence for this is weak⁹. The mean metallicity increases by about an order of magnitude, from $Z \approx 0.1 Z_{\odot}$ or slightly less at $z \approx 2$ to $Z \approx Z_{\odot}$ at $z = 0$ ^{10,11}. The mean dust-to-gas ratio increases by a similar factor, while the mean dust-to-metals ratio remains roughly constant at about the present value in the local ISM^{10,11,12}. These results are entirely consistent with the recent Keck observations by Lu et al^{11,13,14}. The abundances of H_2 and CO appear to be much lower at $z \gtrsim 2$ than at $z = 0$ ¹⁵. As a consequence of the relatively small samples involved, most of the numbers quoted here are uncertain by factors of 1.5 or more.

3 Cosmic Chemical Evolution

The global properties defined above are governed by a set of coupled equations, which are sometimes referred to as the equations of cosmic chemical evolution. In the approximation of instantaneous recycling (and $Z \ll 1$), they take the form

$$\frac{d}{dt}(\Omega_g + \Omega_s) = \dot{\Omega}_f, \quad (2)$$

$$\frac{d}{dt}(Z\Omega_g) + (Z - y)\frac{d}{dt}\Omega_s = Z_f\dot{\Omega}_f, \quad (3)$$

where y is the IMF-averaged yield. Equations (2) and (3) are strictly valid only when all galaxies evolve in the same way; otherwise, they should be regarded as approximations. The “source” terms on the right-hand sides of the equations allow for the exchange of material between the ISM of galaxies and the IGM; they represent the inflow or outflow of gas with metallicity Z_f at a rate $\dot{\Omega}_f$. To illustrate a range of possibilities, we consider three types of evolution: a closed-box model ($\dot{\Omega}_f = 0$), a model with inflow of metal-free gas ($\dot{\Omega}_f = +\nu\dot{\Omega}_s$, $Z_f = 0$), and a model with outflow of metal-enriched gas ($\dot{\Omega}_f = -\nu\dot{\Omega}_s$, $Z_f = Z$). Our inflow and outflow models are direct analogs of the standard models of chemical evolution in the disk and spheroid components of the Milky Way^{16,17}. We fix the yield y in each model by requiring $Z = Z_\odot$ at $z = 0$. Then the only adjustable parameters are the “initial” comoving density of gas in galaxies $\Omega_{g\infty}$ (in practice, the value of Ω_g at $z \gtrsim 4$) and the relative inflow or outflow rate ν .

To complete the specification of the models, we make two other approximations, both motivated by the observations summarized in the previous section. (1) We neglect any ionized or molecular gas in the ISM of galaxies and set $\Omega_g = 1.3\Omega_{\text{HI}}$ (to account for He). (2) We assume that just over half of the metals in the ISM are depleted onto dust grains and set $D/G = 0.6Z$. The models are designed to reproduce (as input) the observed decrease in the mean comoving density of HI between $z \approx 3$ and $z = 0$. The only subtlety here is that the observed values of Ω_{HI} tend to underestimate the true values as a consequence of the obscuration of quasars by dust in foreground galaxies¹⁸. We make a self-consistent correction for this bias in the models by linking the obscuration of quasars to the chemical enrichment of galaxies. It is worth noting that, while this correction has a substantial effect on Ω_{HI} , especially at $z \sim 1$, it does not entail large numbers of “missing” quasars (only $\sim 20\%$ at $z = 2$ and $\sim 40\%$ at $z = 4$). The models reproduce (as output) the observed increase in the mean metallicity between $z \approx 2$ and $z = 0$ without any fine tuning of the parameters $\Omega_{g\infty}$ and ν . The reason for this is that most of the star formation and hence most of the metal production occur at $z \lesssim 2$.

Figure 1 shows the evolution of the comoving rate of metal production $\dot{\rho}_z$ in the models. This is given by $\dot{\rho}_z = y\psi$, with $\psi = (1 - R)^{-1}\dot{\rho}_s$ and $\dot{\rho}_s = (3H_0^2/8\pi G)\dot{\Omega}_s$, where $R \approx 0.3$ is the returned fraction. The predicted rates have maxima at $1 \lesssim z \lesssim 2$ and decline rapidly at lower redshifts. Figure 1 also shows estimates of, and lower limits on, $\dot{\rho}_z$ from recent ground-based surveys and the Hubble Deep Field^{19,20,21,22}. These are proxies for global H α and UV emissivities based on the close correspondence between UV emission and metal production in massive stars^{3,22}. Evidently, the predicted and observed rates are in broad qualitative, and even some quantitative, agreement

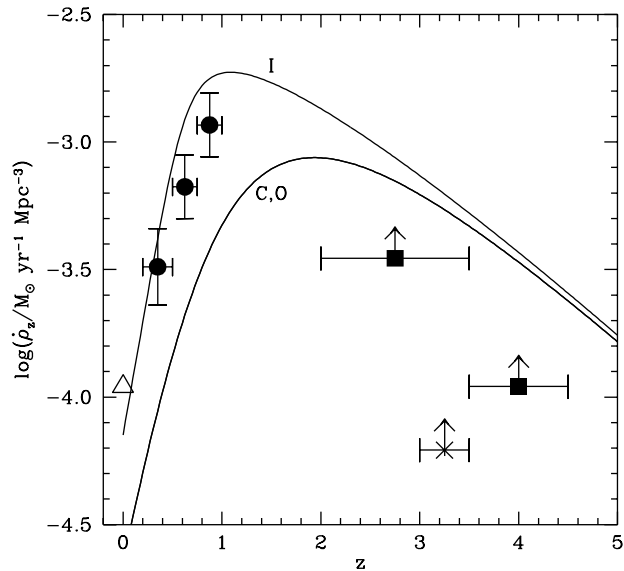


Figure 1: Comoving rate of metal production $\dot{\rho}_z$ as a function of redshift z (for $h = 0.5$, $q_0 = 0.5$, and $\Lambda = 0$). The curves are from the closed-box (C), inflow (I), and outflow (O) models with $\Omega_{g\infty} = 4 \times 10^{-3} h^{-1}$ and $\nu = 0.5$ (see Figure 1 of reference 1). The data points and lower limits represent global H α and UV emissivities from ground-based and *HST* surveys (see Figure 9 of reference 22).

(given the uncertainties in both). This is remarkable because the models were constructed only with absorption-line systems in mind, not the emissivities represented in Figure 1. We have also combined our chemical evolution models with stellar population synthesis models to compute directly the mean comoving emissivity \mathcal{E}_ν at wavelengths from $10^{-1}\mu\text{m}$ to $10^3\mu\text{m}$ and, by an integration over redshift, the corresponding mean intensity of background radiation J_ν . These calculations include a self-consistent treatment of the absorption and reradiation of starlight by the dust within galaxies. The same models shown in Figure 1 also predict a far-IR/sub-mm background in nice agreement with a tentative detection based on *COBE* data²³.

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